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Prepared on behalf of:

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AIR CLEARANCES FOR 50 kV 60 Hz

RAILWAY OPERATIONS

Prepared by:

INSTITUT DE RECHERCHE D'HYDRO-QUEBEC
1800 Montée Ste-Julie
Varennes, Québec JOL 2PO

Principal Investigators: P.J. Lambeth
Nguyen Duc Hai

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PROJECT TEAM

The project team for IREQ was:

Mr. Peter J. Lambeth, Project Leader

Mr. Nguyen Duc Hai

Mr. Robert Lanoie

Dr. Farouk A.M. Rizk, Consultant

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17. Abstract

A study has been made of the effect of various parameters on the electric strength of air gaps to provide a technical basis for the derivation of clearances to be used on the Canadian 50 kV railway system. Tests were made using a rod-plane gap for a range of voltages up to 350 kV_p including switching and lightning impulses as well as 60 Hz and combined impulse and 60 Hz waves. The effects of different atmospheric conditions — clean and salt-water fog and contamination by both conducting and insulating particles as well as exhaust fumes — were investigated. The influence of water droplets falling from one electrode was also determined. Of these, the most important factor in reducing the strength of the air gap was diesel exhaust fumes, which brought down the 60 Hz strength of the gap by as much as 20%.

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17. Résumé

Une étude expérimentale et une recherche bibliographique sur la rigidité électrique d'une distance d'isolement dans l'air sous plusieurs conditions atmosphériques et plusieurs types de pollution a été effectuée afin de déterminer les distances d'isolement du système d'électrification à 50 kV des chemins de fer canadiens. Les essais ont été effectués sur une configuration tige-plan jusqu'à des tensions de 350 kV crête. Les formes d'onde utilisées sont: surtension de manoeuvre, surtension de foudre, AC 60 Hz et la combinaison de AC 60 Hz (50 kV rms) combinée avec une surtension de manoeuvre.

Les essais ont été effectués sous différentes conditions atmosphériques: propre, brouillard propre et brouillard salin. Différents types de pollution comme les particules isolantes, les particules conductives et les gaz d'échappement rencontrés dans les tunnels ont été étudiés également. L'influence de l'égouttement de l'eau sur les électrodes a aussi été abordée. Les essais ont montré que le facteur le plus important, dont il faut tenir compte dans le design de l'isolation, est l'effet du gaz d'échappement des moteurs diesel. Cet effet peut réduire la rigidité électrique en AC de 20% comparativement à celle dans l'air propre.

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SUMMARY

With the object of producing standards for the clearances to be used on the future Canadian 50 kV 60 Hz Railroad System, a study has been made of the effect of various parameters on the electric strength of air gaps.

Particular attention has been paid to the conditions in tunnels, as well as the transient reduction in clearances associated with locomotive movement. Tests were made using a rod-plane gap representing the least favorable geometry for a given clearance, with a range of voltage waves up to 350 kVp including switching and lightning impulses as well as 60 Hz and combined impulse and 60 Hz waves. The effects of different atmospheric conditions — clean and salt-water fog and contamination by both conducting and insulating dust particles as well as exhaust fumes — were investigated. The influence of water droplets falling from one electrode was also determined. Of these, the most important factor in reducing the strength of the air gap was diesel exhaust fumes which brought down the 60 Hz strength of the gap by as much as 20%.

A literature survey showed that high speed air containing large charged particles may also reduce flashover stresses and thus warrant further study.

The results of this work are presented in the form of tables and curves showing the relationship between the mean flashover voltage and clearance for tunnel and outdoor conditions for switching impulse and 60 Hz voltages. At 250 kVp ($\sim$ 3.5 p.u.) clearances are roughly 0.5-0.6 m. Guidance is given on the methods of using these data by applying correction factors to the voltage to allow for effects of altitude, normal air density and humidity variations, the required probability of flashover (or factor of safety), and the effect on flashover probability of having a number of gaps in parallel.

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1. INTRODUCTION

In considering the electrification of the Canadian railway system at an operating voltage of 50 kV rms 60 Hz, the need arises to establish suitable air clearances for use not only in open countryside, but also in tunnels where the provision of space can be very costly.

The work described in this report has been commissioned by the Canadian Electrical Association and Transport Canada, acting on behalf of the subcommittee on standardisation of the committee for Canadian Railway Electrification, to obtain flashover voltage values under conditions simulating the critical situations which may arise in service, to give the necessary design data for the selection of suitable clearances.

At a meeting held in April 1982 a memorandum[1] was presented to IREQ representatives setting out the terms of reference for this study. In this document the key points are the requirements to establish suitable clearance values for use in "static" and "dynamic" conditions. These correspond to normal and absolute minimum values, and broadly to long-term and transient clearances. The conditions for which these values are required include a range of atmospheric conditions, both outdoors and in tunnels.

In discussions it emerged that the actual overvoltages would need to be established, but that a maximum limit of 350 kVp would apply, and that the range of conditions would be so large that a comprehensive study of flashover voltages would be impracticable. Instead it was proposed to limit the work to those conditions which might reasonably be expected to arise, and give more variable or lower flashover stresses and to proceed in sequence to try to determine the worst conditions in this respect, using a single electrode geometry, a rod-plane gap which is known from the literature to have the lowest flashover stress of all simple geometries. The data collected would cover a range of gap spacings so that the results when analysed could be used for any system with a maximum surge voltage not exceeding 350 kVp.

A program was agreed which meets these requirements and is described in detail in the subsequent sections of this report. The report gives the test results, which have been analysed in such a way that they can be readily utilised to derive clearances once the voltage levels, conditions and degree of security of the system have been determined.

Two associated subjects which have been discussed but are not dealt with here are the analysis of the frequency, waveform and magnitude of overvoltages which may be produced and the requirements for the insulators to be used. The former, in particular, is complementary to the present work and in conjunction with it should help in the optimisation of clearances.

2. OBJECT

The object of this project is to provide the necessary data by means of which the electrical clearances for a 50 kV 60 Hz Railway Electrification Scheme can be derived knowing the voltage waveforms and amplitudes. The values were to be obtained mainly by tests supplemented by a study of the literature.

3. TEST PROGRAM

The original program was a sequence of tests on a rod-plane gap, with flashover values obtained for each condition at four gap spacings, up to 1m, using the "up and down" technique to obtain the 50% flashover voltage at each distance and an estimate of standard deviation. The voltage waves applied consisted of power frequency (AC), i.e. 60 Hz, switching impulse (SI) and lightning impulse (LI) and combinations of power frequency and impulse. Details of the waveforms and test techniques are given in section 4 "Testing procedure".

The first set of nine tests were made with AC, SI and LI on the rod-plane gap in

(i) clean dry conditions
(ii) clean fog
(iii) salt-water fog

These and the other test conditions are also described in section 4.

The second set of two tests was to be on the worst of the three atmospheric conditions with combinations of AC and SI and AC and LI. The third set of eight tests was to be selected from combinations of test conditions involving water dripping from the end of the rod electrode at three different rates, various durations of AC and the voltage waveform giving the lowest flashover stress in the first two test sequences. This was to simulate the wet conditions which obtain in many tunnels.

The fourth set of four tests was to be with two different gas mixtures, representing typical or extreme atmospheric conditions in tunnels with two critical voltage waveforms. The fifth set of four tests was to be in dry conditions with dust pollution, both of insulating and conducting particles and again with two critical voltage waveforms.

In addition, a literature survey was to be made of the effect on gap breakdown of air velocity, and also of electrically charged particles.

The original program has been adhered to in essence, although minor modifications have been made both in furtherance of the primary objective and to facilitate testing. For example, not all tests were repeated at four gap spacings when it was clear that there would be no benefit from this; additional tests were made which were

more relevant and some test conditions were modified or dropped. The changes will be apparent from the results presented in Section 5.

4. TESTING PROCEDURE

The rod-plane gap used was made up from a 6 cm diameter cylindrical tube terminated with a cone of half-angle 15° and with its axis perpendicular to the plane of a large metal sheet. In dry and fog tests the rod was supported vertically between two parallel strings of cap-and-pin insulators. Two large reservoirs balanced on each side of the rod were used to supply the water for the dripping tests. After various techniques were tried the best method for obtaining a uniform flow of water from the tip was found to be to use a short length of capillary tubing supplied via a needle valve and a Tee-piece from the reservoirs to limit the flow to the desired rate. The water was fed into layers of blotting paper wrapped around the cone but behind its point in order to spread the flow and reduce its velocity.

For the gas and solid particle tests a special box was constructed, a 2.5 m cube (see Fig.1). On one side there is the metal sheet (plane), and a bushing on the opposite face supports the rod. Provision is made for gas inlet and outlet. With the rod/plane axis horizontal dust particles can be fed into the gap from above using a hopper with an automatic distributor. In practice it was found that the dust particles eventually chosen were too fine to be fed in this way and the dust was kept in the air by means of a jet of compressed air playing on the particles which had fallen to the bottom of the box.

The voltages for the tests consisted of 60 Hz AC supplied by a 0-550 kV transformer. The switching impulse and lightning impulse waveforms were double exponential with approximate times to crest respectively of 100 and 1.2 μsec and times to half value of 2 500 and 50 μsec. These are standard waveforms in accordance with Document 60.2 of IEC, and IEEE standards and the waveforms used are within the tolerances specified.

To measure the flashover voltages the "up and down" method[2] was used. In this technique a voltage is applied at an estimate of the flashover value. If a flashover results the next application is at a value reduced by one step. If the application withstands then the voltage is raised the next time. This sequence is repeated and results in values which are distributed about the mean flashover value. The sequence starts with the first result which differs from that obtained previously. Fifty(50) valid tests were made for each gap distance at each test condition. The voltage step used was roughly equal to the standard deviation to give the best estimates for V_{50} , the mean flashover voltage, and σ, the standard deviation, and the

95% confidence limits of these values have been calculated according to the methods of Dixon and Mood[2].

The individual tests using impulse voltages were single impulses of the required crest value. For the 60 Hz voltage the test consisted of an application of voltage starting from zero and increasing at a rate of 5.5 kV rms/sec, maintaining the voltage constant for 60 secs if no flashover occurred, and reducing the voltage immediately to zero. For some tests with water droplets longer dwell times were also used.

For combined AC and impulse voltages the AC voltage was maintained at 50 kV rms., and the impulse was applied at the positive peak of the 60 Hz wave.

For impulse voltages the polarity in every case was positive, to give the lower flashover voltage. The rod was always the energized electrode, the plane was grounded.

For the salt fog used in the first set of tests the standard method described in IEC Document 507[3] was used, with a salinity of 160 Kg/m^3. In this procedure[4] the test object is between two vertical arrays of sprays 3m on each side of it and with individual jets spaced 0.6 m apart vertically. The sprays are fed with salt (NaCl) water, at 0.5ℓ/min for each spray and this is atomized by a jet of compressed air directed towards the gap. The modal fog droplet size is ≈4 μm, with 2% of droplets exceeding 50 μm diameter and the liquid water content about 5 g/m^3. The air in the gap region is turbulent with a velocity of about 1.5 m/s.

The clean fog, also used in the first set of tests, is produced by injecting steam into the test chamber near ground level, through 2 cm diameter pipes. This produces a fog of 8 μm mean droplet size and water density of 4 g/m^3, but with relatively little air movement[5]. There is a temperature rise in the chamber due to the use of steam which gives an increase of 18°C in an hour from the start of steam injection.

The fogs were produced in a test chamber 4.7 m x 4.7 m x 4.7m, and the gap was in the centre of this chamber. The upper electrode was initially connected to the voltage source by a wall bushing, but during the testing this punctured and a new bushing had to be fabricated to continue the tests. This improvised bushing was satisfactory for impulse voltages but was not capable of withstanding the full 350 kV at 60 Hz during fog; and it was not possible, therefore, to carry out the tests on the maximum gap length in these conditions.

5. TEST RESULTS

The flashover voltages of air gaps are known to be a function of air density and humidity. They are thus dependent an temperature and pressure as well as humidity.

Conversion factors are used to convert a measured value, V, to a value at standard temperature, pressure and humidity V_0, where the standard values are:

Temperature, t_0 = 20°C
Pressure, P_0 = 101.3 KPa (760 mm Hg)
Humidity, h_0 = 11 g water vapour/m^3.

The air density conversion factor K_d is given by

$$K_d = P/P_0 \times \frac{273 + t_0}{273 + t}$$ for gaps up to 1m in length.

The humidity correction factor K_h is taken from a curve (Figure 2)[6] and $V_0 = \frac{K_h}{K_d} \cdot V$

The measured voltages have all been corrected for density (K_d) and humidity (K_h), except for those values obtained in fog conditions in the first test series which have been corrected for density only.

The results for the first set of tests in the dry, salt fog and clean fog are shown in Figs. 3, 4, and 5 for AC, LI and SI respectively and in Table 1, which gives the complete test results.

Since the dry condition was found in general to give the lowest flashover stresses the next tests were done in this condition with a combination of 50 kV 60 Hz and SI. The results are shown in Fig.6, together with the curves for V_{50} obtained for the same atmospheric condition with AC, SI and LI. For this and all subsequent tests a small number of AC tests were made in clean dry atmospheric conditions immediately before testing for a new variable, as a check that no new source of error had appeared.

Tests were then made with water dripping from the upper conical electrode at various rates. It was intended to vary the time of AC voltage application to see what effect this would have on the motion and shape of hanging water droplets and hence on the breakdown voltage, but in fact at a relatively low AC voltage the stress at the point was enough to break up the droplets immediately. A few tests with 2 minute application of AC showed that the flashover voltage was not significantly altered. Tests with varying durations of AC were therefore, abandoned and the water droplet tests were made with AC of one minute dwell time, (Fig.7) and with 50 kV rms + SI, (Fig.8), over the range of flow rates from infrequent individual drops to a continuous water flow from the electrode when it was unenergized. In addition, the effect of increased water conductivity was investigated by using salt water, as well as plain tap water.

Tests were then carried out in the box on two gas mixtures. This entailed the use of a horizontal gap which modified the field slightly because of the presence of the floor as an additional ground plane. Measurements of the AC and the SI flashover voltages for the horizontal gap were first made. The box was then completely filled with gasoline exhaust fumes from a four-stroke engine and the flashover voltages measured. These tests were repeated with diesel exhaust fumes.

These results are given in Figures 9 and 10 for AC and SI respectively. Since it was suspected that the fumes might act as condensation nuclei and that the size of the water droplets might be critical in influencing the flashover voltage a small amount of steam (10 g/m^3) was gradually introduced into the box with the diesel exhaust. The precise effect of this could not be established, since the droplet size will vary with time, but the tendency was for a slight increase in withstand voltage rather than a decrease.

The next series of tests involved the introduction of insulating and conducting particles into the gap. Wheat flour and coal dust were used since these are commonly transported on the railways. Both were so fine that they could be kept in suspension by compressed air blowing onto the floor of the box. The particle size distribution was, for the flour: 4% 5-10μm, 4% 10-15μm, 11% 15-25μm, 43% 25-50μm, 37%, >50μm and for the coal dust: 74% 5-10μm, 15% 10-15μm, 0.7% 15-25μm, 0.2% 25-50μm, 0.07% >50μm. The amount in suspension is estimated at 5 g/m^3 and 3 g/m^3 respectively. The flashover voltages for AC are shown in Fig. 11. Fig. 12 shows photomicrographs of the flour and coal dust. The test in the coal dust was terminated prematurely due to the ignition of the dust by the discharge, which burned the plastic sheet and damaged the surface insulation in the box. However, this test, like that with flour, had shown no significant effect on the flashover voltage.

6. DISCUSSION

6.1 Voltage waveforms

The voltage waveforms used to establish clearances in this test program correspond broadly to the range of waveforms which may be encountered on a typical distribution network. The one minute 60 Hz test corresponds to two operational conditions, one when a temporary overvoltage is produced either due to a fault on another phase or to transformer energization, usually lasting much less than a minute admittedly, but more particularly to the condition when a pantograph on a locomotive approaches a grounded electrode and the gap reduces to a minimum and then increases again, thus over-stressing the gap at 60 Hz for a short period. The switching and lightning impulses are standard waveforms accepted by IEC and IEEE as giving sufficiently close approximations to the actual waveforms corresponding to switching and lightning transients for test purposes[7]. As the results demonstrate, the flashover voltage is not sensitive to waveform up to the 1m gap length. It was anticipated that a combination of 60 Hz voltage to provide a continuous stress and a switching impulse might be dangerous for a gap in which a water drop was hanging from one electrode, and as this is a common stress combination it was used for these tests.

Positive polarity was used for the impulses throughout the tests, because although negative flashover values may be much reduced in fog[5], for example, they are still substantially above the positive flashover valves.

Similarly, AC tests in fog were not made with long durations. Although the breakdown strengths may be reduced as the duration increases[5] they will still not be critical in the determination of clearances which will be decided by transient, i.e. passing, values or by impulse values in the static condition. In considering the behaviour of the gap when subjected to different voltage waveforms most weight has been given to the response to switching surges since these will almost certainly decide the static clearances, particularly in tunnels.

6.2 Electrode Profile

The choice of a rod-plane gap as the only electrode system was based partly on the need to reduce the number of parameters in the program as far as possible, but mainly on the recognition that this is not only the most severe condition for a simple geometry with a given spacing, but also one to which many geometries approximate, particularly under wet conditions.

It is easy to see that a pointed icicle or a pantograph horn close to a tunnel wall give similar geometries, but in fact Rizk[8] has shown that the effect of rain on long gaps with a variety of electrode profiles has been to degrade them all to a similar level with a flashover stress of about 4 kVp/cm. Figure 13 has been taken from his paper, and the characteristic corresponding to this stress has been added to demonstrate how well the positive SI values fit it: the value of 4 kVp/cm is close to that found for most conditions in this work. Another curve from this paper also shows how well the 60 Hz rms rod-plane values dry, agree with the 60 Hz rms 1m sphere-plane values wet (Figure 14). Thus,although the use of rod-plane gap flashover values may be regarded as conservative it can not be considered extreme.

6.3 Fog conditions

Fog will be encountered not only outdoors but more frequently perhaps in tunnels. Although some measurements have been made of air rod-plane breakdown with clean fog[5], and salt fog[9] there are data lacking up to 1m lengths, and indications of high dispersions of V_{50}[9].

Using the best fit curves as a basis for comparison, the results (Figs. 3, 4 and 5) with all three basic waveforms (AC, SI and LI) showed that the highest values were reached in the clean fog. On average the increases were 5, 25 and 35% respectively over the dry condition. This result is consistent with that obtained earlier with the large test chamber[5], although the percentage difference is rather greater. This may well be due to the high and increasing value of the temperature in the test chamber which rose ≈10°C over the period of test, reaching 40°C. At this value with 100% RH (for which no correction is made) the water vapour content will exceed 50 g/m^3, even if the liquid water content is unchanged. Extrapolating the correction curve (Fig. 2) shows that this would involve an increase in flashover voltage of ~ 20% for AC and even more for SI.

The LI values for all conditions were well above those for SI, and so were not critical. The SI values for salt fog were consistently above those for dry conditions by 5-9%, in line with values found by Ely and Roberts[9], but the AC values were almost the same for these two atmospheric conditions, with the salt fog marginally lower on average by 1-2%. Standard deviation was slightly more for the salt fog than in dry conditions, and much greater for the clean fog, probably because of the increase of temperature with time.

Because the condition giving the lowest flashover voltages for SI was the dry one, this was used for the test with a combination of 50 kV rms and SI (Fig. 6). The values obtained were close to those for SI alone but on average 3% lower, an insignificant change.

6.4 Water Drops

Water drops on a h.v. electrode have been found to reduce the effectiveness of a well-designed electrode system[8], and it is also known that under electric stress droplets distort and elongate[10]. The water drip rate and water conductivity might be critical in modifying the effective shape and length of the electrode. Water can be present in tunnels and give high flow rates of conducting water, although outdoors flow rates might be lower. A continuous stream of water from an electrode must be avoided since, if high enough, the flow could short out a gap completely. But dripping should be considered an acceptable risk, and results were evaluated on this basis.

In fact it was found that varying the drip rate over the range 0.16 mℓ/min (40 drops/min) to 20 mℓ/min did not significantly alter the flashover voltage, either with AC or with 50 kV rms combined with SI (Figs. 7 and 8). Only when the flow was increased to 200 mℓ/min corresponding to a steady flow of water, rather than dripping, was there a significant reduction in the flashover voltage. The use of more conducting salt water (260 Kg/m^3, NaCℓ) tended to reduce the voltage a little more, but not to a significant extent. Drop elongation did not take place as expected. Instead, the water drops broke up completely when the AC voltage on the electrode reached 12-20 kV rms, the exact value depending on the gap length. Above this voltage large drops were not seen to form, the water simply spraying off the point in very minute drops, without affecting the flashover voltage of the gap with either AC or SI superposed on AC.

It appears that, with the highly divergent field at the point, droplet instability begins so far below the flashover level that the water drop has no appreciable effect on flashover.

6.5 Gas Contamination

Although in the open air gaseous contamination of a gap is likely to be very little, in a semi-enclosed environment such as a tunnel it is easy to achieve a build up of contamination, especially of exhaust fumes. Since diesel locomotives will use electrified track for several years at least it seemed appropriate to study the effect of diesel exhaust, and gasoline exhaust was also investigated. A literature survey[11] showed that relatively few commonly-occurring gases have breakdown strengths much below that of air, which has a value very close to that of nitrogen, its major component (≈ 80%). Of these few gases with low breakdown strengths CO_2 is one having a strength of 0.88 of that of nitrogen. An internal combustion engine

converts most of the oxygen (≈ 20% of the air) to CO_2, with approximately 1% CO and some water vapour. It seemed likely therefore that any effect of the gas would be small, perhaps a 2-3% change in flashover voltage, even if the exhaust gases were not diluted with air. Consequently the test box was completely filled with exhaust gases and fumes for the test.

It turned out however that the exhaust gas and fumes gave the largest reduction of all in the AC flashover values. For both diesel and gasoline engine exhausts the voltage was reduced by 20% at 1m, with little or no effect at 25 cm, (Fig.9). This reduction seems to be due to space charge build up since the SI values were not reduced at all. Exhaust gases contain fumes, particles of less than 1 μm in diameter, which might act as charge carriers, with a mobility which could be critical with AC at particular gap lengths. Although the make-up of these particles will differ with the two fuels no difference was observed in the flashover voltages for gasoline and diesel fumes. To see whether there might be a further reduction in electric strength by increasing the size of these particles by allowing them to act as condensation nuclei 10 gram/m^2 of steam was gradually introduced into the diesel exhaust gas, but with no adverse effect, possibly because the water already present from the combustion process was already enough for condensation.

Since for these and subsequent tests the gap had to be used in a horizontal position the dry flashover characteristic was remeasured. The effect of the additional ground plane was to reduce the AC flashover voltage slightly (≈ 4% at the highest gap setting).

In service an atmosphere of exhaust fumes would be unbreathable and only a small percentage of the concentration used would be the tolerable limit. However, it should be noted that the effect is almost certainly not linear with concentration and after the box had been left open overnight it was still possible to notice, at the start of the next day, a reduction in flashover voltage from the traces of exhaust fumes. These effects may in fact be caused by fume particles as well as, or instead of, by the gas. This is a subject which might well repay more detailed study.

A practical factor which should also be considered is the effect of the exhaust gas temperature. The exhaust gases collected were cooled and a temperature correction was made for the tests, but in a confined space such as a tunnel hot exhaust gases might reach a gap without appreciable cooling: the effect on gas temperature of a stationary or slow-moving diesel locomotive in a tunnel should be taken into account.

Luckily, transient clearance reductions which will be associated with pantograph movement will not apply with a diesel locomotive and the most critical voltage waveform is likely to be the SI, which was unaffected by the presence of exhaust gases.

6.6 Particle Contamination

References in the literature to the effect of dust particles are superficially conflicting, Schulz[12] showing that the presence of laboratory dust increases the AC breakdown strength of a rod-rod gap, while Elrefaie[13] on the other hand found that particles in rod-plane and other gaps reduce the AC flashover voltage, although the smaller the particle and the more inhomogeneous the field the less the effect will be. Neither reference gives an indication of a change of more than a few percent for dust particles and a rod-plane gap.

The tests carried and both with wheat flour, mean particle size ≈ 50 μm, density estimated at 5 g/m^3 of air, and coal dust, mean particle size ≈ 8 μm, and density estimated at 3 g/m^3 of air, showed no significant change in the flashover voltage for the longer gaps. The AC voltage/length characteristic was linear and so the short gaps showed a slight reduction in voltage compared with the clean dry air condition, which has a slightly non-linear characteristic.

6.7 Gas Velocity

It might be expected that flashover voltage would increase with gas velocity because of the more rapid dispersal of ions from the most critical position. Schulz[12], using a 500 mm rod-rod gap found no effect from air velocities below 1m/sec., but a gradual increase in AC flashover voltage as the velocity increased, amounting to 4% at 2 m/sec, with the air flowing across the gap.

Awad et al.[14] using natural sandstorm conditions and a rod-rod geometry studied the effect of orientation of the wind to the gap axis, and found the lowest flashover values with the wind along the axis of the gap. They also found, contrary to Schulz, that the flashover voltage reduced with increase in velocity, and for a 10 m/s velocity the reduction was 35% for a multidirectional set of gaps. However, it is not clear how much this effect was due to the presence of large charged sand particles.

6.8 Particle Charge

The effect of particle charge on the breakdown strength of gaps has been studied by Elrefaie[14]. Using relatively large insulating particles (0.2 mm dia. sand),

charged by falling through an energized mesh he studied their effect on the breakdown of a gap of up to 100 mm length between a square-ended rod and a plane. Without the particles, this had a strength substantially above that of a point-plane gap, and he reports that the reductions of ≈ 50% in flashover voltage of the rod-plane gap did not reduce the values to below those obtained with the point-plane gap. In fact the use of compressed air to agitate the wheat flour in the box in the current tests almost certainly produced friction charging of the flour particles, and after the end of the test it was possible to see particles of flour clustered on the rod electrode. Like so many of these field-distorting features, these charged particles do not appear to have had a significant influence on the flashover voltage of the rod-plane gap.

However, Elrefaie and Awad et al. between them have indicated that large charged particles could have a substantial effect on breakdown voltage perhaps in association with high speed air. It is clear that such particles need a high speed to remain in the air for any length of time, and to be charged by friction. The association of high speed air and charged large particles is therefore a natural one. If this combination merely reduces the behaviour of a rod-rod gap, say to that of a rod-plane gap, then the clearance values obtained in the present investigation can be used with confidence, but there is no real justification for this assumption. Consequently, if there is a likelihood of this combination of factors arising often enough in association with low clearances then the electrical behaviour of gaps in these conditions should be investigated further.

7. UTILISATION OF TEST DATA

The purpose of this section is to provide a logical basis for the calculation of clearances based on the data produced from the tests.

Table 2 and Fig. 14 have been compiled from these data and consist of V_{50} values for AC and SI (including 50 kV rms + SI) obtained for conditions giving the lowest flashover voltages for each clearance, using the best fit curves and interpolating to get the distance for each voltage level. Subdividing the conditions into "tunnel" and "outdoor" was done by assuming all tests of the appropriate voltage waveform were relevant to tunnel conditions, with the exception of the water-drip tests at 200 mℓ/min; and that for outdoor conditions the exhaust fume conditions were also not relevant. V_{50} values are given both in kV_p, and as per unit values, referred to the peak nominal operating voltage as unity, (i.e. 50 $\sqrt{2}$ kV).

To find a clearance from the table the voltage needs first to be corrected by use of a number of multiplying factors before the clearance can be read off from the appropriate column.

Suggestions for calculating these factors are given below.

7.1 Altitude Factor

A moderate increase in altitude corresponds to a reduction in air density given by the following approximate relationship: relative air density $\Delta_A = 1 - A \times 10^{-4}$ where A is the height above sea level in metres.

Since flashover voltage is proportional to air density, a constant, K_A, can be defined by which, V, the maximum peak voltage should be multiplied to give a voltage having the same flashover clearance at sea level, as the voltage, V, will have at altitude, A.

This constant, $K_A = \dfrac{1}{1 - A \times 10^{-4}}$

7.2 Atmospheric Condition Factor

Another factor which needs to be assessed is that due to the day-to-day variation in air density and humidity at a given site. The correction factor can be derived from atmospheric temperature, pressure and absolute humidity, in accordance with the existing standards[6], i.e. the use of a factor K_v, where

$$K_v = \frac{273 + t}{293} \cdot \frac{760}{P} \times K$$

where t is ambient temperature in °C
P is ambient pressure in mm Hg

and K is obtained from Fig.2.

As an indication of a limit which might be used, Beausejour[15] has calculated a value for K_v based on the most unfavorable combinations of temperature, pressure and humidity for the Province of Québec over the past 3 years. The maximum value he obtained was K_v= 1.16 for 60 Hz, and K_v= 1.12 for SI. The particular weather condition was 99.9 KPa (749.5 mm Hg) temperature 30°C, absolute humidity 3.3 g/m^3. Such extreme values should probably only be used for fixed gaps with a constant, or frequently applied, voltage, e.g. 60 Hz. However, some allowance for variations in atmospheric conditions should be made in any statistical approach to clearance calculations.

7.3 Statistical Factors

The values in Table 2 correspond to a 0.5 probability of flashover for a single voltage application. For extreme surge amplitudes it may be acceptable to use this probability, but for commonly occurring surge levels a lower value will be needed to keep the frequency of flashover to an acceptable figure. A calculation of flashover frequency requires a knowledge of the frequency distribution of the surge amplitudes on the system. If this is not available a common practice is to work to V_m, the maximum SI value on the system, and select a gap length for which this will give a low flashover probability, p.

Depending on p, and assuming a normal distribution of the flashover voltages for a given gap the correction factor, K_p, can be obtained by which V_m can be multiplied to get the appropriate clearance from Table 2.

K_p is given by

$$K_p = \frac{1}{1 - z\sigma/100}$$

where σ is the standard deviation as a percentage of V_m and z is obtained from tables of the cumulative normal distribution function for the particular value of p. Values of z are given in Table A-I of the Appendix as the top line (n = 1) for various probabilities (p_n).

Thus, for example, for $\sigma = 3\%$, $p = 0.1$ $K_p = 1.04$
and $\sigma = 6\%$, $p = 0.01$ $K_p = 1.16$

These corrections apply only for a single gap. If there are several gaps in parallel another additional factor, K_g, should be used as well. The derivation of K_g is given in the Appendix.

The values of σ to be used for K_p and K_g depend on the waveform and differ for various weather conditions. The "up-and-down" method is better designed for measuring V_{50} than σ, but for most SI tests a value of $\sigma = 6\%$ was not exceeded, and for AC a rather lower value of 4%. Tolerances on these values were typically ± 50% from individual test runs and it is suggested that 6 and 4% should be used in calculating K_p.

8. CONCLUSIONS

The flashover distances for a rod-plane gap under unfavourable atmospheric conditions have been obtained for a range of voltages up to 350 kV, both for AC and impulse voltages, and a composite table embodying the most significant results is presented.

The withstand clearances can be derived from the actual voltage level V, corrected to V'

by $V' = K_A \cdot K_V \cdot K_p \cdot K_g \cdot V$

where K_A is an altitude factor

K_V is atmospheric density and humidity factor

K_p is a Safety factor

K_g is a factor dependant on the number of gaps in parallel.

The appropriate clearances are shown in Table 2 for values of V' in 10 kV steps.

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APPENDIX

The effect of gaps in parallel

The withstand values derived in the main text are obtained by considering the performance of a single gap, and the probability of its flashing over with a single application of voltage. This will be relevant if one gap is reduced substantially by a particular occurrence; an icicle, or the passage of a pantograph horn past a grounded post, for example. If, however, a number of equivalent gaps are subjected to the same voltage a correction has to be made to take account of the increased probability of flashover from the multiplicity of gaps. This probability, p_n, is given by: $p_n = 1 - (1 - p)^n$ where p = probability of flashover of a single gap and n = the number of gaps in parallel.

This simplifies to

$$p_n \simeq np \quad \text{where} \quad np \ll 1$$

Thus for $p_n = 0.01$ we get the withstand voltage,

$$V_W = \begin{cases} V_{50} - 2.32\sigma & \text{for } n = 1 \\ V_{50} - 3.09\sigma & \text{for } n = 10 \\ V_{50} - 3.75\sigma & \text{for } n = 100 \end{cases}$$

assuming a normal distribution for the flashover voltage.

The results of these calculations can be presented in the form of correction factors, K_g, by which K_p. V for a single gap can be multiplied to give the corresponding voltage for a number of parallel gaps having the same probability of flashover.

The value of K_g for a value of p_n, n and σ can be found from the expression

$$K_g = \frac{1 - q_n\,\sigma}{1 - q_1\,\sigma}$$

using Table A - I to obtain q_1, the value corresponding to a single gap and q_n, the value corresponding to n gaps. Thus, for example, for $p_n = 0.1$ n = 10, $K_g = \frac{1 - 2.31\sigma}{1 - 1.28\sigma}$

TABLE A-I

Values of q_1 and q_n

n \ p_n	0.5	0.1	0.05	0.01	0.001
1	0	1.28	1.645	2.325	3.09
3	0.82	1.82	2.13	2.72	3.40
10	1.50	2.31	2.57	3.09	3.71
30	2.00	2.70	2.93	3.40	3.99
100	2.46	3.06	3.29	3.71	4.26
300	2.83	3.40	3.59	3.99	4.50
1000	3.20	3.72	3.89	4.26	4.75

TABLE 1A

TEST RESULT SUMMARY: 60 Hz Flashover Values

Dry and fog

Dry Clean

D (CM)	$V_{50}\pm\Delta V$ (Kv peak)	$\sigma\pm\Delta\sigma$ (%)
25	124± 1	1± 1
25	126± 2	2± 1
50	232± 1	1± 1
50	236± 1	1± 1
50	215± 2	1± 1
75	352± 1	1± 1
75	353± 1	1± 1
100	466± 2	1± 1
100	466± 2	1± 1

Clean Fog (Steam)

D (CM)	$V_{50}\pm\Delta V$ (Kv peak)	$\sigma\pm\Delta\sigma$ (%)
25	126± 8	16±10
50	242± 5	6± 4
65	322± 8	6± 4

Salt Fog (160Kg/m^3)

D (CM)	$V_{50}\pm\Delta V$ (Kv peak)	$\sigma\pm\Delta\sigma$ (%)
25	111± 1	3± 2
50	231± 1	1± 1
60	273± 4	3± 2

Water drip

Tap Water
Drip rate .16ml/min

D (CM)	$V_{50}\pm\Delta V$ (Kv peak)	$\sigma\pm\Delta\sigma$ (%)
25	126± 1	1± 1
25	126± 1	1± 1

Tap Water
Drip rate .36ml/min

D (CM)	$V_{50}\pm\Delta V$ (Kv peak)	$\sigma\pm\Delta\sigma$ (%)
25	130± 2	2± 2

Tap Water
Drip rate 20ml/min

D (CM)	$V_{50}\pm\Delta V$ (Kv peak)	$\sigma\pm\Delta\sigma$ (%)
25	126± 1	1± 1
50	239± 7	5± 4

Tap Water
Drip rate 200ml/min

D (CM)	$V_{50}\pm\Delta V$ (Kv peak)	$\sigma\pm\Delta\sigma$ (%)
25	113± 2	3± 3
50	217± 3	1± 1
75	316± 4	2± 2

Saline solution(260Kg/m^3)
Drip rate 200ml/min

D (CM)	$V_{50}\pm\Delta V$ (Kv peak)	$\sigma\pm\Delta\sigma$ (%)
25	103± 2	2± 1
50	210± 4	3± 3
75	313± 8	5± 4
100	451± 3	1± 1

TABLE 1A (contd.)

TEST RESULT SUMMARY: 60 Hz Flashover Values

Exhaust Gases

Dry Clean Hor.Gap

D (CM)	$V_{50}\pm\Delta V$ (Kv peak)	$\sigma\pm\Delta\sigma$ (%)
25	124± 3	2± 2
25	118± 2	2± 2
25	127± 1	1± 1
50	247± 3	1± 1
50	237± 2	1± 1
75	338± 2	1± 1
75	347± 2	1± 1
75	359± 3	1± 1
100	467± 9	3± 3
100	435± 7	2± 2

Diesel Fume Hor.Gap

D (CM)	$V_{50}\pm\Delta V$ (Kv peak)	$\sigma\pm\Delta\sigma$ (%)
25	122± 2	2± 1
50	213± 4	4± 3
75	293± 3	2± 1
100	337±15	10± 7
100	379±26	12±12

Gasoline Fume Hor.Gap

D (CM)	$V_{50}\pm\Delta V$ (Kv peak)	$\sigma\pm\Delta\sigma$ (%)
25	130± 1	2± 1
25	131± 2	2± 1
50	216± 1	1± 1
50	215± 2	2± 1
75	291± 2	1± 1
75	285± 2	1± 1
100	378± 3	1± 1

Particles

Wheat flour Hor.Gap

D (CM)	$V_{50}\pm\Delta V$ (Kv peak)	$\sigma\pm\Delta\sigma$ (%)
25	109± 2	2± 2
25	116± 1	2± 1
50	225± 6	4± 4
50	226± 2	1± 1
50	225± 4	3± 2
50	234± 2	1± 1
50	229± 2	1± 1
75	342± 1	1± 1
75	348± 2	1± 1
75	347± 1	1± 1
100	457± 9	3± 3
100	458± 7	1± 2

Coal Dust Hor.Gap

D (CM)	$V_{50}\pm\Delta V$ (Kv peak)	$\sigma\pm\Delta\sigma$ (%)
25	123± 1	1± 1
50	242± 2	1± 1

TABLE 1B

TEST RESULT SUMMARY: Lightning Impulse Flashover Values

Dry and fog

Dry Clean

D (CM)	$V_{50} \pm \Delta V$ (Kv peak)	$\sigma \pm \Delta\sigma$ (%)
12.5	98± 3	10± 7
22.5	129± 2	4± 2
25	147± 3	5± 3
25	147± 2	2± 1
50	260± 2	2± 1
75	370± 2	1± 1
90	443± 3	1± 1

Clean Fog (Steam)

D (CM)	$V_{50} \pm \Delta V$ (Kv peak)	$\sigma \pm \Delta\sigma$ (%)
25	197± 4	5± 3
25	191± 3	4± 3
50	359± 6	5± 3
60	426± 6	4± 2

Salt Fog (160Kg/m^3)

D (CM)	$V_{50} \pm \Delta V$ (Kv peak)	$\sigma \pm \Delta\sigma$ (%)
25	181± 4	5± 3
25	180± 6	8± 6
50	293± 4	3± 2
60	353± 6	4± 3

TABLE 1C

TEST RESULT SUMMARY: Switching Impulse Flashover Values

Dry and fog

Dry Clean

D (CM)	$V_{50} \pm \Delta V$ (Kv peak)	$\sigma \pm \Delta\sigma$ (%)
12.5	80± 1	3± 2
25	136± 2	4± 2
25	138± 1	2± 1
50	240± 2	2± 1
50	256± 2	2± 1
50	246± 2	2± 1
75	336± 4	3± 1
75	341± 7	4± 3
100	420± 5	4± 2

Clean fog (Steam)

D (CM)	$V_{50} \pm \Delta V$ (Kv peak)	$\sigma \pm \Delta\sigma$ (%)
25	195± 6	9± 6
50	303± 5	5± 3
75	410±11	7± 5

Salt Fog (160Kg/ml^3)

D (CM)	$V_{50} \pm \Delta V$ (Kv peak)	$\sigma \pm \Delta\sigma$ (%)
25	151± 3	5± 3
50	269± 6	5± 3
75	350± 5	4± 2

Exhaust Gases

Dry Clean Hor.Gap

D (CM)	$V_{50} \pm \Delta V$ (Kv peak)	$\sigma \pm \Delta\sigma$ (%)
25	141± 3	2± 2
25	137± 3	4± 3
50	254± 3	2± 2
75	324± 4	3± 2
75	351± 8	5± 4
100	439±17	8± 7
100	449±10	4± 4

Diesel Fume Hor.Gap

D (CM)	$V_{50} \pm \Delta V$ (Kv peak)	$\sigma \pm \Delta\sigma$ (%)
25	143± 4	5± 4
50	263± 2	2± 1
75	365±20	13±10
100	445± 6	1± 1

Gasoline Fume Hor.Gap

D (CM)	$V_{50} \pm \Delta V$ (Kv peak)	$\sigma \pm \Delta\sigma$ (%)
25	142± 4	7± 4
50	263± 7	8± 4
75	342± 4	2± 2
100	440± 8	5± 3

TABLE 1D

TEST RESULT SUMMARY: 50 Kv rms plus Switching Impulse Flashover Values

Dry

Dry Clean

D (CM)	$V_{50}\pm\Delta V$ (Kv peak)	$\sigma\pm\Delta\sigma$ (%)
25	130± 2	5± 3
25	130± 1	1± 1
50	234± 3	3± 2
50	249± 4	3± 2
75	332± 6	5± 3
75	328± 9	5± 4
100	418± 4	2± 1

Water Drip

Tap Water Drip rate .16ml/min

D (CM)	$V_{50}\pm\Delta V$ (Kv peak)	$\sigma\pm\Delta\sigma$ (%)
25	130± 3	6± 4
50	242± 7	6± 5
50	241± 4	5± 3
70	320± 6	5± 3

Tap Water Drip rate .36ml/min

D (CM)	$V_{50}\pm\Delta V$ (Kv peak)	$\sigma\pm\Delta\sigma$ (%)
50	246± 4	4± 2
70	324±11	8± 5

Tap Water Drip rate 20ml/min

D (CM)	$V_{50}\pm\Delta V$ (Kv peak)	$\sigma\pm\Delta\sigma$ (%)
50	243± 7	7± 4
70	324± 4	3± 2

Saline Sol. (260Kg/m^3) Drip rate 200 ml/min

D (CM)	$V_{50}\pm\Delta V$ (Kv peak)	$\sigma\pm\Delta\sigma$ (%)
25	115± 2	3± 3
50	242± 4	3± 2
75	329± 7	5± 3

TABLE 2

Clearance/V_{50} values for worst test condition

Voltage Level (kV peak)	Clearance Requirement (cm)		
	AC 60 Hz Tunnel	AC 60 Hz Outdoor	Switching Impulse Tunnel/outdoor
0	0.	0.	0.
10	2.3	2.3	1.7
20	4.5	4.5	3.5
30	6.7	6.7	5.3
40	9.0	9.0	7.1
50	11.2	11.2	9.0
60	13.4	13.4	10.9
70	15.6	15.6	12.8
80	17.8	17.8	14.7
90	20.0	20.0	16.7
100	22.2	22.2	18.7
110	24.4	24.4	20.7
120	26.6	26.6	22.8
130	28.8	28.8	24.9
140	31.3	31.0	27.0
150	33.9	33.2	29.1
160	36.5	35.3	31.3
170	39.2	37.5	33.5
180	42.0	39.7	35.7
190	44.8	41.8	38.0
200	47.6	44.0	40.3
210	50.4	46.1	42.6
220	53.4	48.3	44.9
230	56.3	50.4	47.3
240	59.3	52.6	49.7
250	62.4	54.7	52.1
260	65.5	56.9	54.6
270	68.6	59.1	57.1
280	71.8	61.2	59.6
290	75.1	63.4	62.1
300	78.4	65.6	64.7
310	81.7	67.7	67.3
320	85.1	69.9	69.9
330	88.5	72.1	72.6
340	92.0	74.2	75.4
350	95.5	76.4	78.2
360	99.0	78.6	81.3
370	102.7	80.7	84.3
380	106.3	83.0	87.3
390	110.0	85.4	90.4
400	113.8	87.9	93.6
410	117.5	90.4	96.8
420	121.4	92.9	100.0
430	125.3	95.4	103.2
440	129.2	97.9	106.5
450	133.2	100.5	109.9
460	137.2	103.0	113.2
470	141.3	105.6	116.7
480	145.4	108.2	120.1
490	149.5	110.0	123.6
500	153.7	113.4	127.2

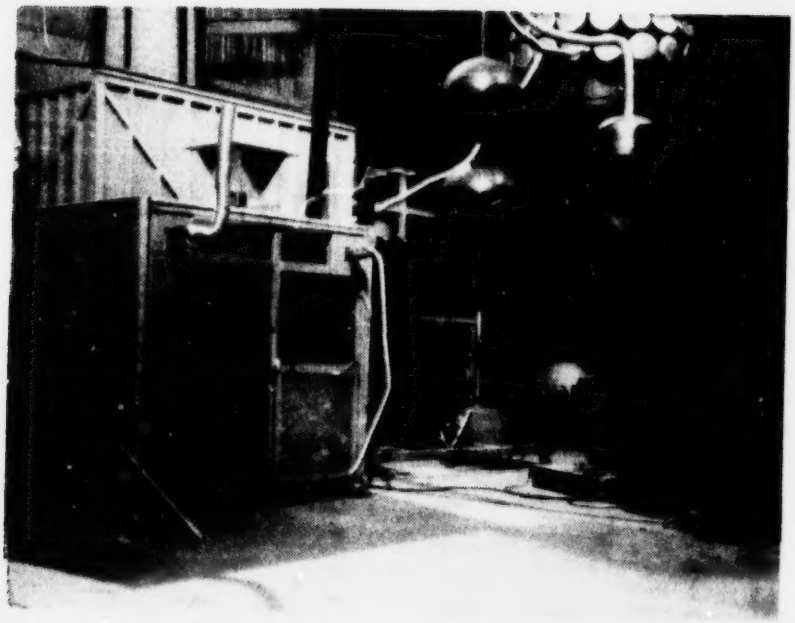


Fig. 1 Enclosure used for particle and gas tests with transformer

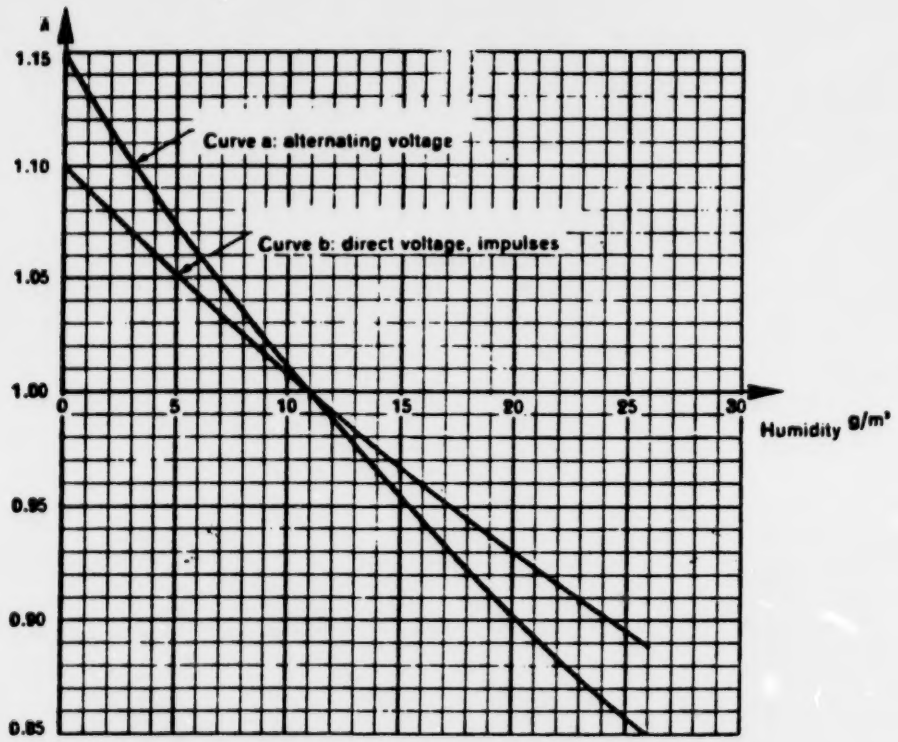


Fig. 2 Humidity Correction Factor K_h as a Function of Absolute Humidity (Ref. 6)

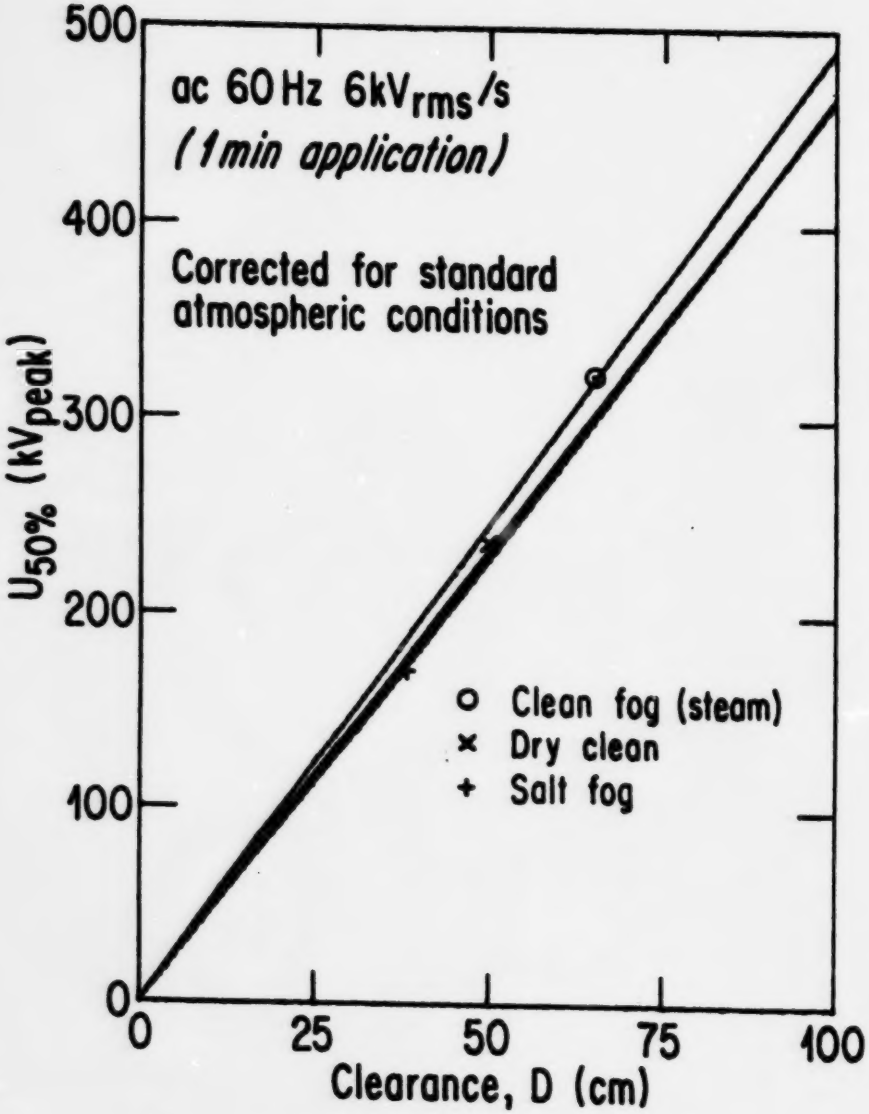


Fig. 3 Effect of dry and fog conditions on AC flashover voltage

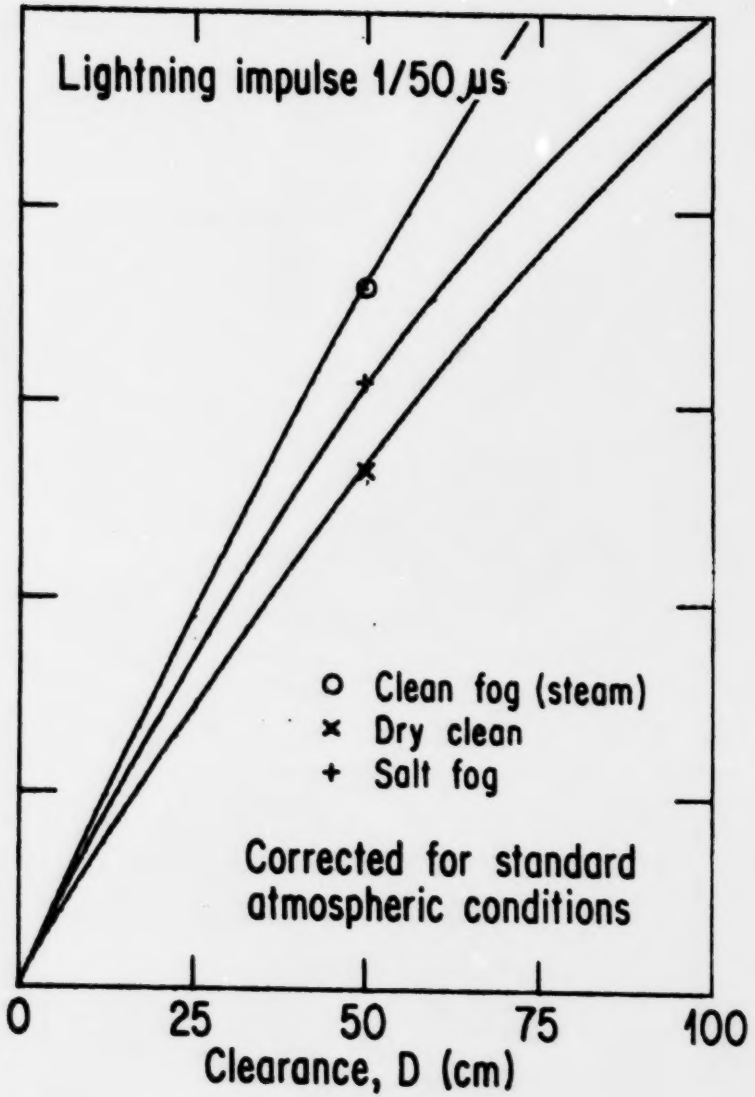


Fig. 4 Effect of dry and fog conditions on lightning impulse flashover voltage

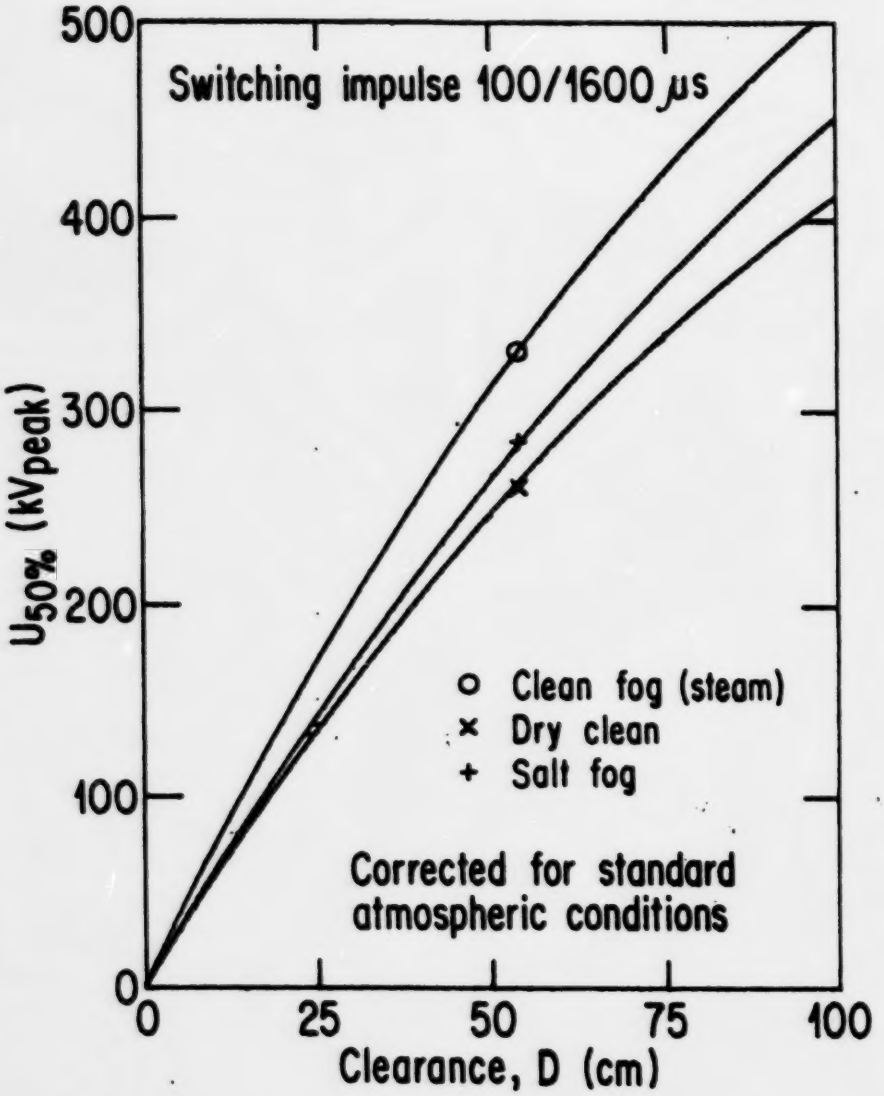


Fig. 5 Effect of dry and fog conditions on switching impulse flashover voltage

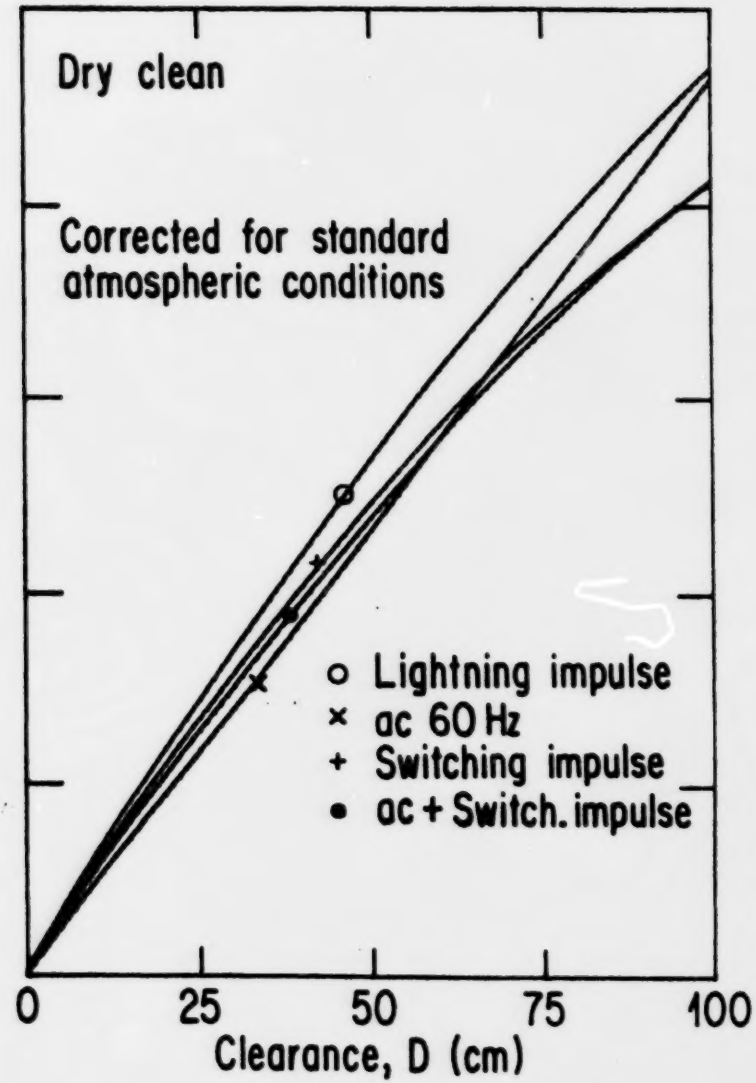


Fig. 6 Flashover voltages in dry conditions for AC plus switching impulse, and other voltage waveform

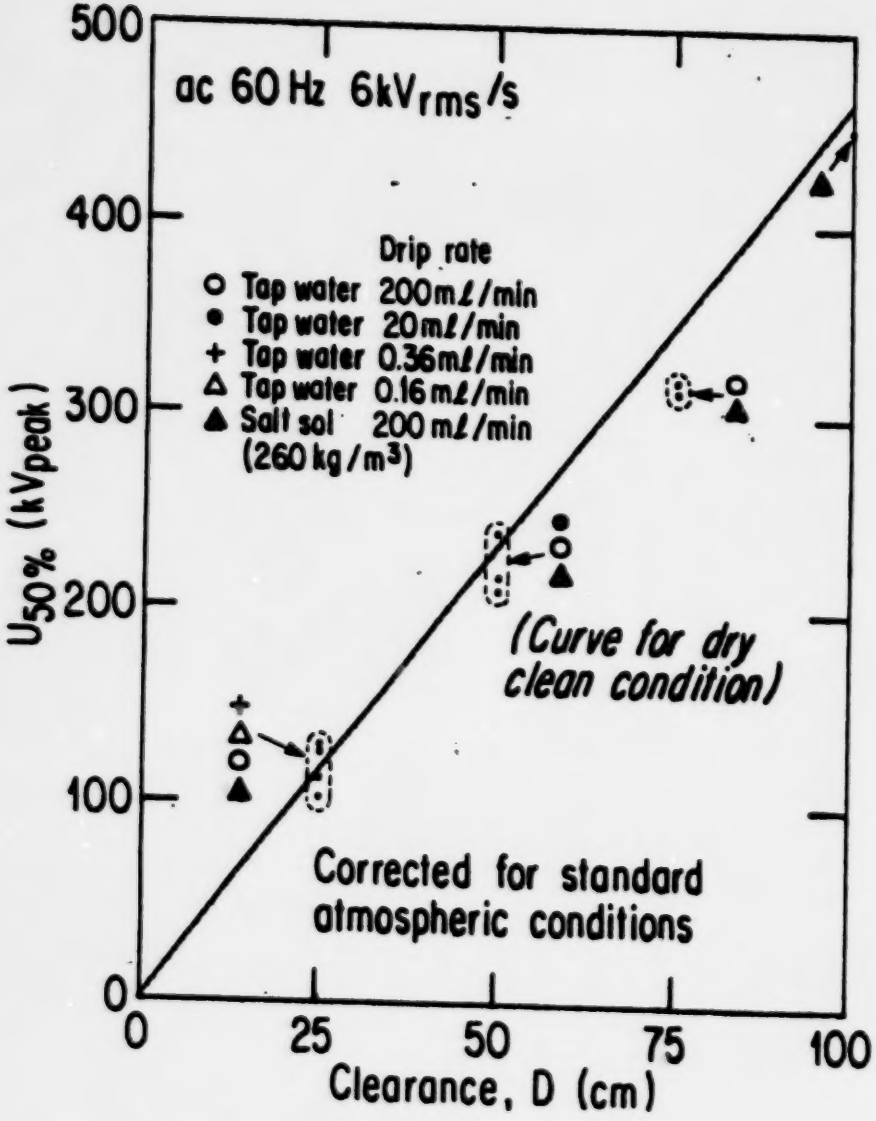


Fig. 7 AC flashover voltage for various dripping conditions

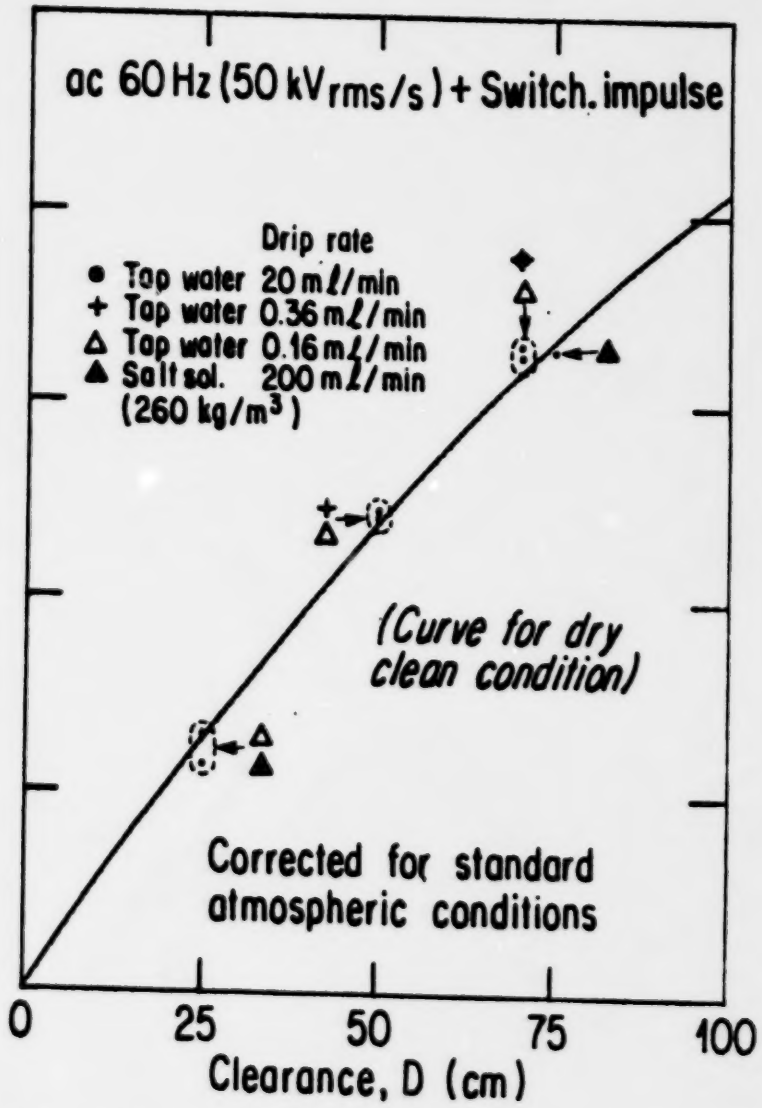


Fig. 8 AC and switching impulse flashover voltage for various water dripping conditions

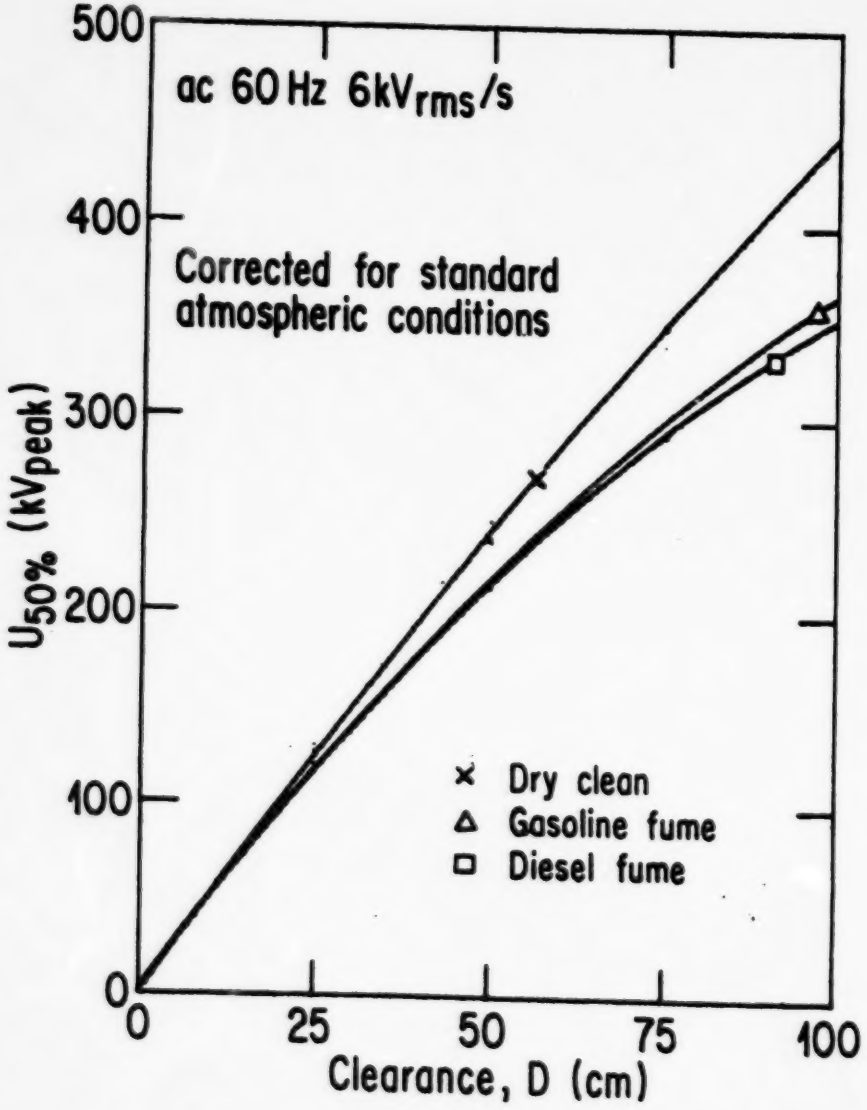


Fig. 9 Effect of exhaust fumes on AC flashover voltage

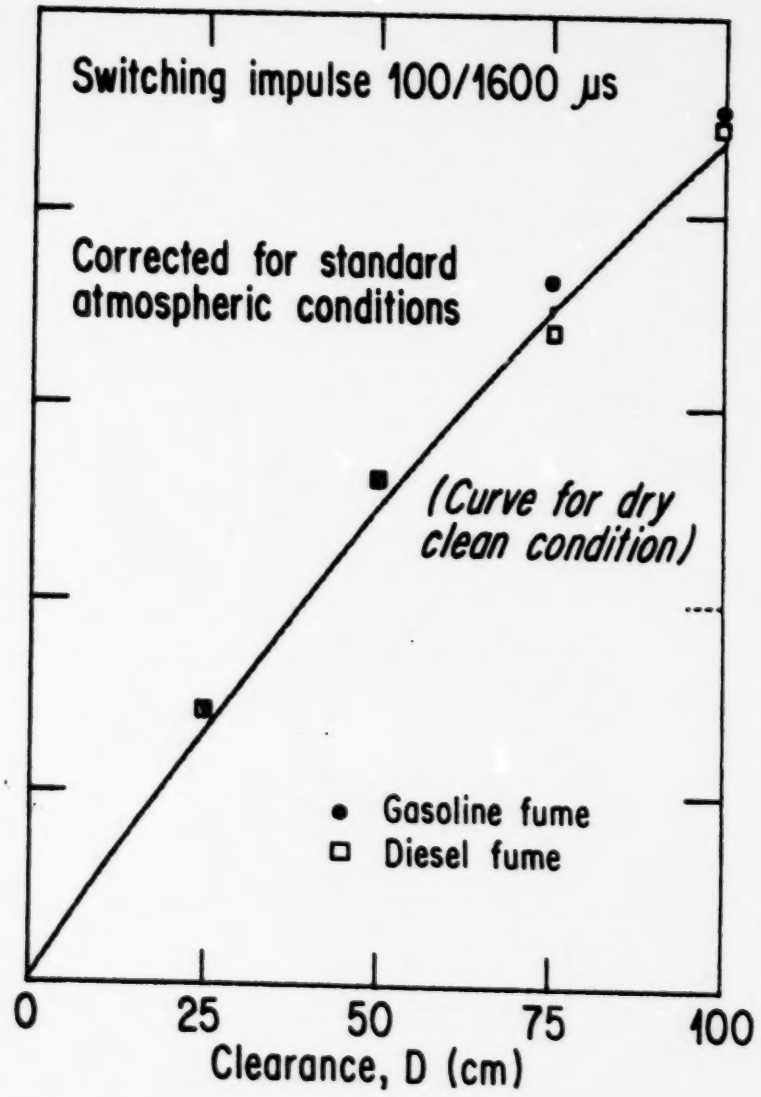


Fig. 10 Effect of exhaust fumes on switching impulse flashover voltage

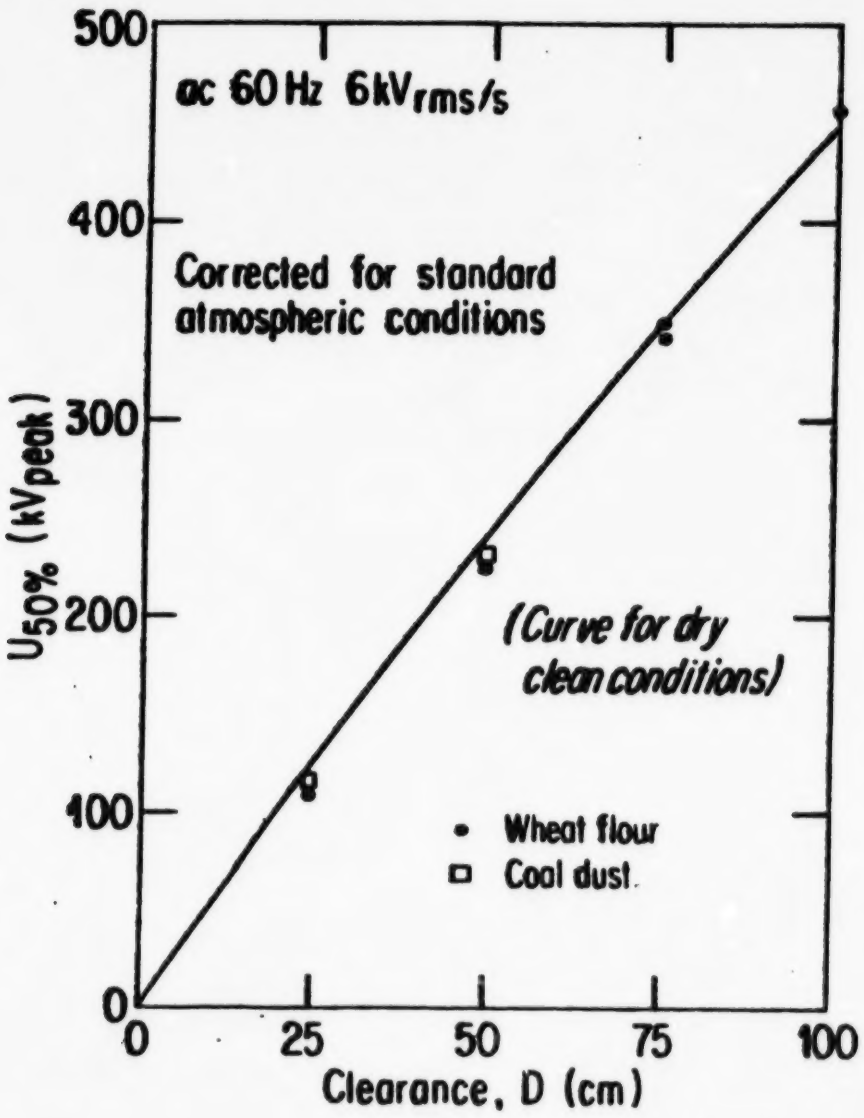
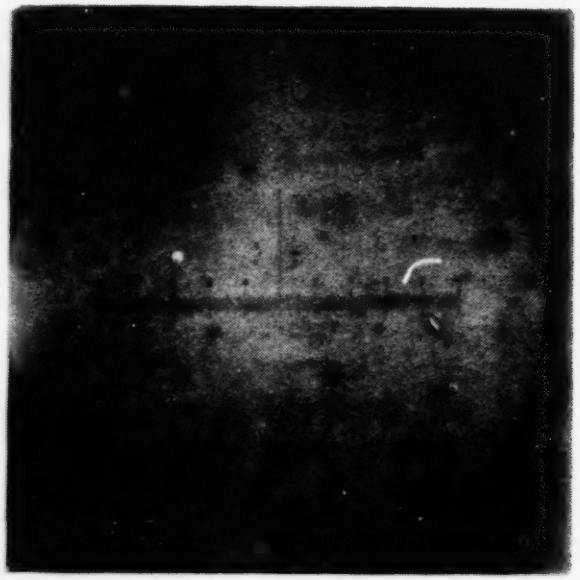
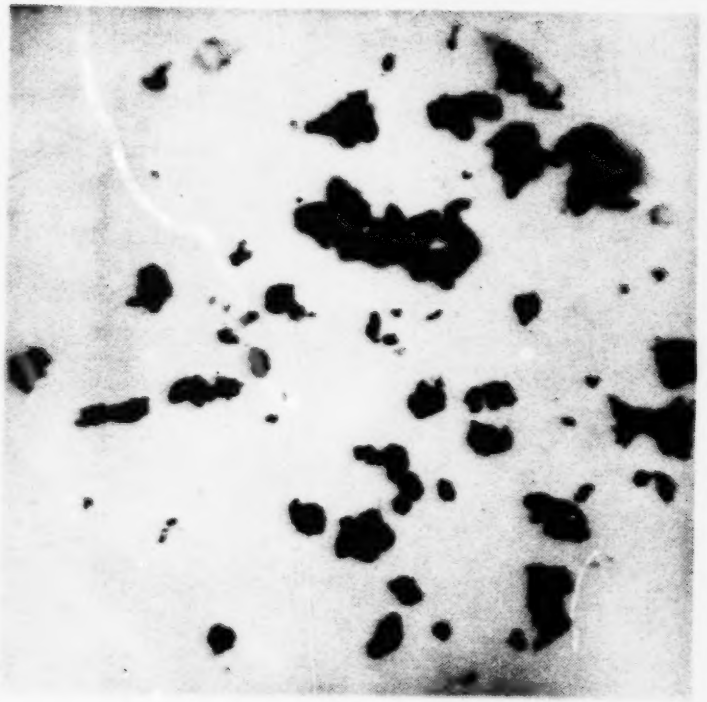


Fig. 11 Effect of particles on AC flashover voltage



a - Coal dust particles
x 42



b - Wheat flour particles
x 58

Fig. 12 Photomicrographs of particles
(a) Coal dust (x 42)
(b) Wheat flour (x 58)

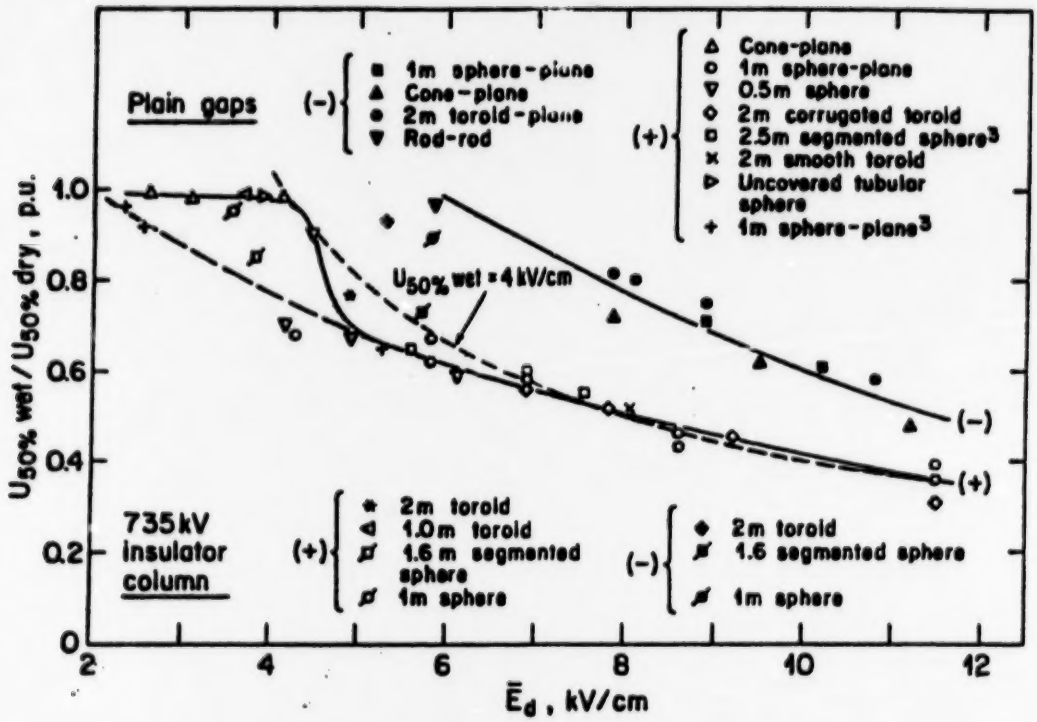


Fig. 13 Influence of rain on flashover stress for large gaps (reference 8)

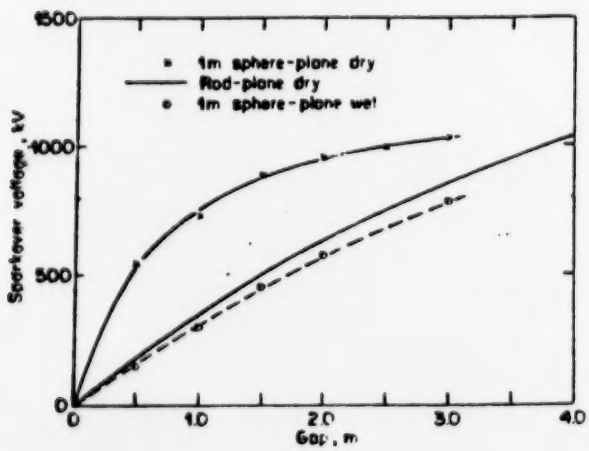


Fig. 14 Dry and Wet 60 Hz Sparkover Characteristics of Large Air Gaps (Ref. 8)

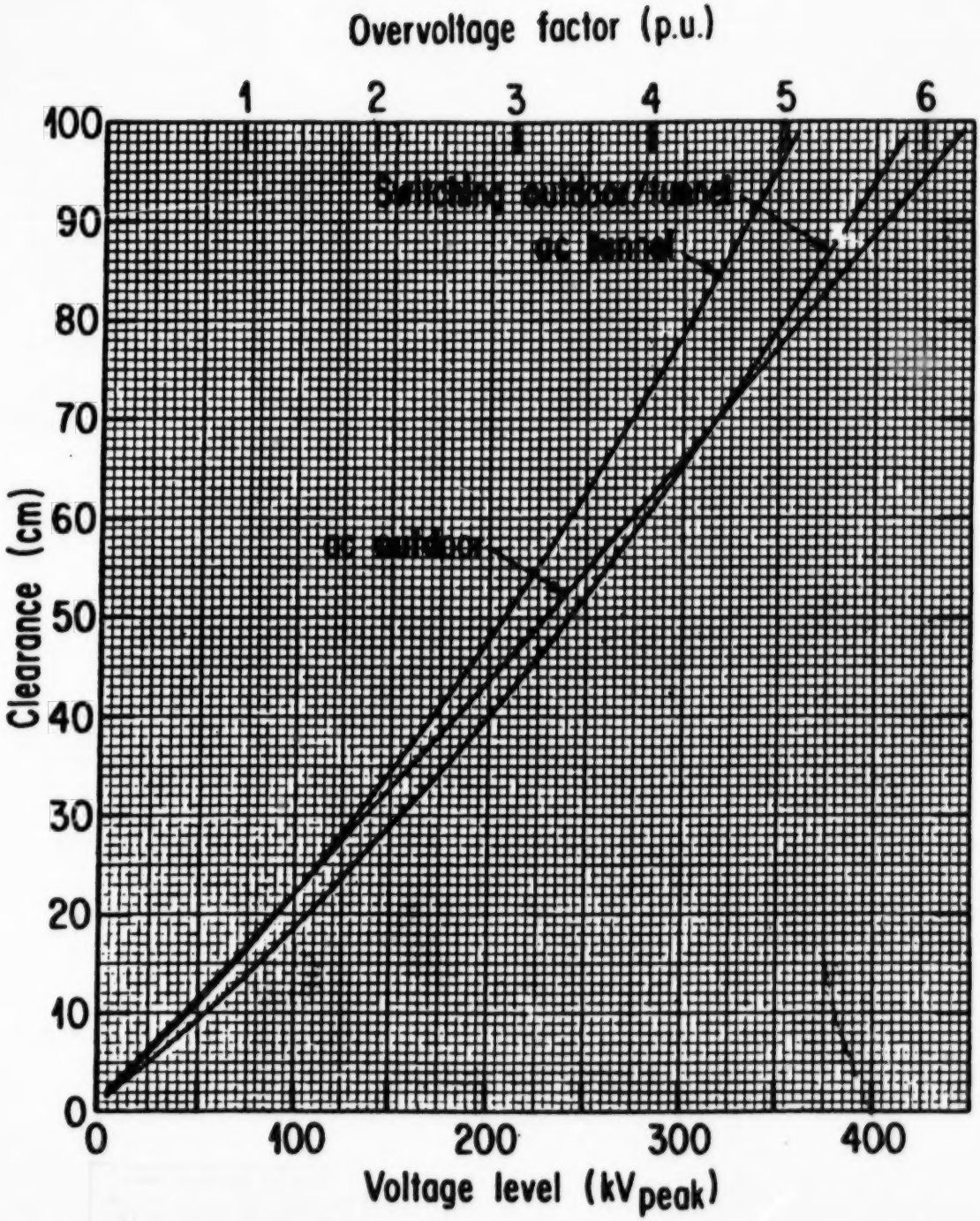


Fig. 15 Clearance (cm) $/V_{50}$ curves for the worst test conditions